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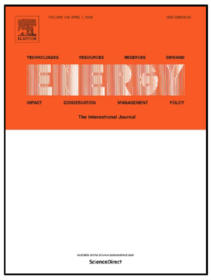

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Dynamic thermal performance of horizontal ground source heat pumps – The impact of coupled heat and moisture transfer

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ABSTRACT
A ground heat exchanger is a key component of a ground source heat pump system, and heat and moisture transfer occurs simultaneously in soil with a horizontal ground heat exchanger in operation. A new method has been developed to generate moisture and temperature profiles in soil with spatially and temporally varying properties. The profiles are used as initial data for accurate solution of the equations for transient heat and moisture transfer in soil containing a buried horizontal ground heat exchanger. The impacts of initial conditions of soil and coupled heat and moisture transfer are assessed on the thermal performance of a horizontal ground heat exchanger for a ground source heat pump for different installation depths and soil textures. Seasonal heat transfer through a horizontal heat exchanger increases with installation depth and a heat exchanger installed at 2 m deep can transfer 19% more heat than that at 1 m deep. Heat transfer in sandy soil is 17% higher than in loamy sand soil which is 14.5% higher than in clay loam soil. The maximum differences between models with and without moisture transfer for the prediction of heat transfer through a heat exchanger are 24%, 17% and 18% in clay sand, loamy sand and sandy soils, respectively. In conclusion, it is necessary to use a coupled heat and moisture transfer model in order to predict accurately the seasonal thermal performance of a ground heat exchanger in shallow ground.

KEYWORDS: Ground heat exchanger; heat and moisture transfer; ground-source heat pump; seasonal performance; spatiotemporal variation; soil properties.

1. INTRODUCTION
A ground-coupled heat exchanger is a key component of a ground source heat pump (GSHP) for heating and cooling of a building or provision of hot water. A ground heat exchanger can be installed vertically or horizontally and a horizontally coupled heat exchanger would experience more variations with time and space in the temperature, moisture and associated thermosphysical properties of surrounding soil.

Extensive research has been conducted on the performance of vertical borehole heat exchangers. These include experimental measurements [1-3], analytical or semi-analytical solution or coupled with numerical modeling mainly in terms of g-functions [4-9] and numerical simulation [10-11]. The performance of horizontal heat exchangers for GSHPs has also been studied using experimental measurements and mathematical models, though not as extensive as for the more widely used borehole heat exchangers. A horizontal heat exchanger for a GSHP can be formed with parallel straight pipes or slinky coils and by comparison only a limited number of field tests have been carried out for horizontal straight pipes [12-13], slinky coils [14-15] and both types [16].

Experimental measurements are useful for determination of the performance of a horizontal heat exchanger and for validation of a mathematical model. However, long-term performance can be measured practically only on site and data from field measurements of soil properties are rather limited, often for a few points before installation, and location specific. Mathematical models can be used to gain a better understanding of heat transfer between soil and a ground heat exchanger and provide data for more detailed analysis and prediction of its performance. Such a heat transfer model can be derived analytically for one-dimensional heat transfer in soil of homogeneous properties under special boundary condition [17]. For multi-dimensional heat transfer involving complex interactions with atmosphere and the heat exchanger, a numerical method would be required [12, 14, 18-21].

However, because of the spatial and temporal variation of moisture, the thermal and physical properties of soil in shallow ground are not homogeneous even if the distribution of solid matter is homogeneous. Nayler, et al [22] monitored the thermal properties of soil in the Midwestern USA at depths of 1.2 m, 1.5 m and 1.8 m and found that soil-moisture fluctuations resulted in soil thermal conductivity variability by an average of 27%. Therefore, in order to predict accurately the thermal performance of a ground heat exchanger, a time-dependent numerical model should include coupled heat and moisture transfer in soil. Numerical models for coupled heat and moisture transfer have been developed previously for horizontal ground heat exchangers with relatively simple initial conditions such as a uniform moisture and temperature or a temperature profile in the computational domain [23-25].

The accuracy of a numerical solution of transient transport phenomena is influenced not only by the model equations and the solution method but also by the initial conditions for soil temperature and moisture in shallow ground [23, 26]. Kopecky [27] showed that the initial soil temperature was one of the most important parameters that would influence the total heat exchange through a horizontal heat exchanger for a given period. There are analytical expressions for vertical soil temperature variation typically in a sinusoidal form which may be used to set the initial soil temperature at the start of system operation, for example

$$T = T_m - T_{amp} e^{-Z/D} \sin\left((t - t_0)\frac{2\pi}{365} - \frac{Z}{D} - \frac{\pi}{2}\right) \tag{1}$$

where T is the soil temperature (°C) at depth Z (m) and time t (day). T_m is the annual mean temperature of deep soil (°C), T_{amp} is the annual amplitude of surface temperature (°C), t_o is the time lag from a starting date to the occurrence of the minimum temperature in a year (day) and D is the damping depth (m) of annual fluctuation.

This type of expression is derived for soil with homogeneous properties. Therefore, it may not be able to represent the temperature of soil where soil moisture and associated thermophysical properties are not constant in time or deviate considerably from their typical values. Ozgener, et al. [28] showed that when such an expression was fitted to real soil temperature measurements there would be errors between 10% and 15% in terms of the magnitude of annual variation but the resulting errors could be much higher in terms of daily mean variation, e.g. an absolute error of 6°C compared with a daily mean variation of 12.3°C, i.e. nearly 50% error.

Soil moisture variation is more complex mathematically than the temperature. There is no equivalent analytical expression for spatiotemporally varying soil moisture and consequently different approaches have been adopted for prescribing the initial soil moisture for computer modelling. The simplest method is to set a uniform soil moisture level for the whole computational domain, in the absence of on-site measurement. A more sophisticated one is to specify a non-uniform distribution based on the solution of Richards equation [29] for vertical variation (increase) of liquid moisture from soil surface to a depth of water table [30-31]. This can be accomplished if the depth of water table as well as soil properties is known for a given site. However, there are uncertainties associated with this approach. For example, the water table depth is highly dependent on a location and also varies considerably with time (season). Besides, this type of profile could not take full account of daily or seasonally varying ambient and soil conditions. In addition, the moisture content in real soil with a ground heat exchanger does not necessarily increase with depth monotonically [32].

Hence, there are two main objectives of this work. One is to develop a new methodology for generating vertical soil moisture and temperature profiles that can be used for initialisation of dynamic thermal simulation of horizontal ground heat exchangers. The profiles account for spatiotemporally varying soil properties. Another objective is to evaluate the impact of moisture transfer on the dynamic thermal simulation of these heat exchangers through comparison between heat transfer models with and without moisture transfer.

2. METHODOLOGY

Accurate prediction of the dynamic thermal performance of a horizontal ground heat exchanger requires not only capturing transient heat and moisture transfer in soil and accounting for spatially and temporally varying soil properties but also spatially varying soil conditions at the beginning of operation.

2.1 Model equations for heat and moisture transfer in soil

The mathematical model is based on the work by Philip and de Vries [33] who developed the general equations for heat and moisture movement in porous materials such as soil under combined temperature and moisture gradients. The model equations for heat and moisture transfer in soil containing a ground heat exchanger are derived below with the following assumptions [26]:

- Dry solid matter in a control volume is homogenous, isotropic and stationary.
- Radiation heat transfer between soil particles is negligible.
- There is no hysteresis between drying and wetting processes.
- External pressure for water movement is absent.
- Effects of solutes are negligible.

2.1.1 Equation for moisture transfer

Consider moisture transfer in a control volume at the steady state which can take place in both vapour and liquid phases. Vapour transfer is driven by the temperature gradient and moisture gradient:

$$\dot{Q}_v = -D_{T,v}\nabla T - D_{\Theta,v}\nabla\Theta \tag{2}$$

where $\dot{Q}_v$ is the volumetric vapour flux (m^3/m^{2}s), $D_{T,v}$ is the thermal vapour moisture diffusivity (m^2/sK), $D_{\Theta,v}$ is the isothermal vapour moisture diffusivity (m^2/s) and Θ is the volumetric moisture content (m^3/m^3).

Liquid transfer is induced not only by the temperature and moisture gradients but also by the gravity represented by the hydraulic conductivity:

$$\dot{Q}_l = -D_{T,l}\nabla T - D_{\Theta,l}\nabla\Theta - K\vec{i} \tag{3}$$

where $\dot{Q}_l$ is the volumetric liquid flux (m^3/m^{2}s), $D_{T,l}$ is the thermal liquid moisture diffusivity (m^2/sK), $D_{\Theta,l}$ is the isothermal liquid moisture diffusivity (m^2/s), K is the hydraulic conductivity of soil (m/s) and $\vec{\mathrm{i}}$ is the unit vector in the vertical z direction.

The total moisture movement is the sum of vapour and liquid transfer, $\dot{Q} = \dot{Q}_l + \dot{Q}_v$:

$$\dot{Q} = -\left(D_{T,l} + D_{T,v}\right)\nabla T - \left(D_{\Theta,l} + D_{\Theta,v}\right)\nabla\Theta - K\vec{i} \tag{4}$$

According to the mass balance, the rate of moisture change in a control volume is equal to the sum of the net rate of moisture flow into the volume and the rate of moisture injection into or extraction from the volume, i.e.

$$\frac{\partial(\rho_l\Theta)}{\partial t} = -\nabla\cdot(\rho_l\dot{Q}) + \rho_l S_\Theta \tag{5}$$

where ρ_l is the density of liquid moisture (kg/m^3) and S_Θ is the volumetric moisture injection (source) or extraction (sink) (m^3/m^{3}s).

The source (sink) of moisture could result from liquid moisture injection through (drip) irrigation or moisture extraction by plant roots often used for modelling of soil-vegetation systems but not considered here. A moisture source that is more relevant to the present work is potential condensation of moisture on the external surface of the impervious ground heat exchanger.

Assuming that the change in the density of water is negligible (less than 0.2% change for a temperature increase from just above the freezing point to 20°C) and substituting Equation (4) into Equation (5) yields

$$\frac{\partial \Theta}{\partial t} = \nabla \cdot \left(\left(D_{T,l} + D_{T,v} \right) \nabla T \right) + \nabla \cdot \left(\left(D_{\Theta,l} + D_{\Theta,v} \right) \nabla \Theta \right) + \frac{\partial K}{\partial z} + S_{\Theta} \quad (6)$$

2.1.1 Equation for heat transfer

Again first consider heat transfer in the steady state. Heat gain/loss by the soil in a control volume results from sensible heat transfer by conduction due to the temperature gradient and latent heat transfer by vapour movement due to the moisture gradient:

$$\dot{q} = -\left(k + L\rho_l D_{T,v} \right) \nabla T - L\rho_l D_{\Theta,v} \nabla \Theta \quad (7)$$

where k is the thermal conductivity of soil (W/mK) and $L\rho_l D_{T,v}$ is the contribution to the apparent thermal conductivity by latent heat transfer from vapour movement due to the temperature gradient and L is the latent heat (for evaporation/condensation) or fusion of water (for freezing/thawing) (J/kg).

The energy balance requires that the rate of heat gain or loss in a control volume should equal the sum of the net rate of heat flow into the volume and the rate of heat generation/dissipation in the volume, i.e.,

$$\frac{\partial (\rho C T)}{\partial t} = -\nabla \cdot \dot{q} + S_T \quad (8)$$

where ρ is the density of soil (kg/m^3), C is the specific heat of soil (J/kgK) and S_T is the volumetric source (sink) of heat due to internal heat generation or dissipation (W/m^3).

Unlike the water density, the moisture-dependent soil density and its thermal properties can vary significantly with depth and time as illustrated in Fig. 5 together with Fig. 4. The source or sink of heat is associated with the phase change of moisture from the potential condensation of moisture on the heat exchanger and possible freezing (thawing) of moisture in soil near the ground surface and surrounding the heat exchanger. The process of freezing/thawing of soil moisture can be formulated into Equation (8) with an additional term on the left side, $L\frac{\partial(\rho_i \Theta_i)}{\partial t}$, ($\rho_i$ = ice density and Θ_i = solid moisture content), but this term is taken as part of a source/sink for heat transfer in computer programming. Although heat transfer through the heat exchanger can also be modelled as a heat source/sink, it is more realistic to treat the heat exchanger pipe as a conducting material and its inner surface as a boundary with convection heat transfer.

Substituting Equation (7) into Equation (8) leads to

$$\frac{\partial (\rho C T)}{\partial t} = \nabla \cdot \left(\left(k + L\rho_l D_{T,v} \right) \nabla T \right) + \nabla \cdot \left(L\rho_l D_{\Theta,v} \nabla \Theta \right) + S_T \quad (9)$$

2.1.3 Soil properties

Soil properties such as the density, specific heat, thermal conductivity, hydraulic conductivity and moisture diffusivities are dependent on the moisture content [25]. For example, the soil density, specific heat and thermal conductivity can be expressed explicitly as functions of the volumetric composition of moisture in different states, dry solid matter and gases as follows:

$$\rho = \sum_{m=1}^{n} \rho_m \theta_m + \rho_l \theta_l + \rho_i \theta_i + \rho_p \theta_p \tag{10}$$

$$C = \frac{\sum_{m=1}^{n} \rho_m C_m \theta_m + \rho_l C_l \theta_l + \rho_i C_i \theta_i + \rho_p C_p \theta_p}{\sum_{m=1}^{n} \rho_m \theta_m + \rho_l \theta_l + \rho_i \theta_i + \rho_p \theta_p} \tag{11}$$

$$k = \frac{\sum_{m=1}^{n} f_m k_m \theta_m + k_l \theta_l + f_i k_i \theta_i + f_p k_p \theta_p}{\sum_{m=1}^{n} f_m \theta_m + \theta_l + f_i \theta_i + f_p \theta_p} \tag{12}$$

where θ is the volumetric fraction of a constituent; subscripts m is the m^{th} component of dry soil and l, i and p represent liquid moisture, solid ice and gas-filled pores, respectively. f_i, f_p and f_m are the ratios of the average temperature gradient of the constituent (ice, pores and the m^{th} component of n types of dry soil grains, respectively) to that of water.

The model equations are solved numerically using the control volume method together with the initial and boundary conditions.

2.2 Boundary conditions

A horizontal heat exchanger is represented by a series of straight parallel pipes inside a large extended rectangular computational domain filled with soil. The boundary of the domain includes the top soil surface, the far-field bottom face and four vertical faces as well as the interior and exterior surfaces of heat exchanger pipes and the inlet and outlet openings for the pipes. Fig. 1 illustrates the boundary conditions on a vertical plane normal to a horizontal heat exchanger. The top surface boundary is the most complicated and involves i) coupled heat and moisture transfer by natural convection between the surface and ambient air due to wind and buoyancy effects, ii) solar radiation to the surface and thermal radiation from the surface to the sky, iii) moisture evaporation from the surface to air, condensation from air to the surface, phase change between liquid moisture and solid ice due to possible freezing and thawing and associated heat transfer, iv) heat and moisture from precipitation, and v) heat conduction and moisture diffusion through the surface. Details of the boundary conditions are described in references [19, 25].

2.3 Initial conditions

For simulation of transient heat and moisture transfer through a system of soil and ground heat exchanger for seasonal operation, it is essential to specify soil conditions at the time when the system starts operation as close to real soil at the same instant of a day in a year as possible.

In this work, a new method is developed to establish temperature and moisture profiles for initialisation which are able to take account of instant and varying ambient heat and moisture conditions and consequent varying thermophysical properties of soil. The method is based on simplifying equations (6) and (9) to one dimensional vertical moisture and heat transfer (without the heat exchanger or the associated heat and moisture source/sink) as follows:

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z}\left(\left(D_{T,l} + D_{T,v}\right)\frac{\partial T}{\partial z}\right) + \frac{\partial}{\partial z}\left(\left(D_{\Theta,l} + D_{\Theta,v}\right)\frac{\partial \Theta}{\partial z}\right) + \frac{\partial K}{\partial z} \tag{13}$$

$$\frac{\partial (\rho C T)}{\partial t} = \frac{\partial}{\partial z}\left(\left(k + L\rho_l D_{T,v}\right)\frac{\partial T}{\partial z}\right) + \frac{\partial}{\partial z}\left(L\rho_l D_{\Theta,v}\frac{\partial \Theta}{\partial z}\right) + S_T \tag{14}$$

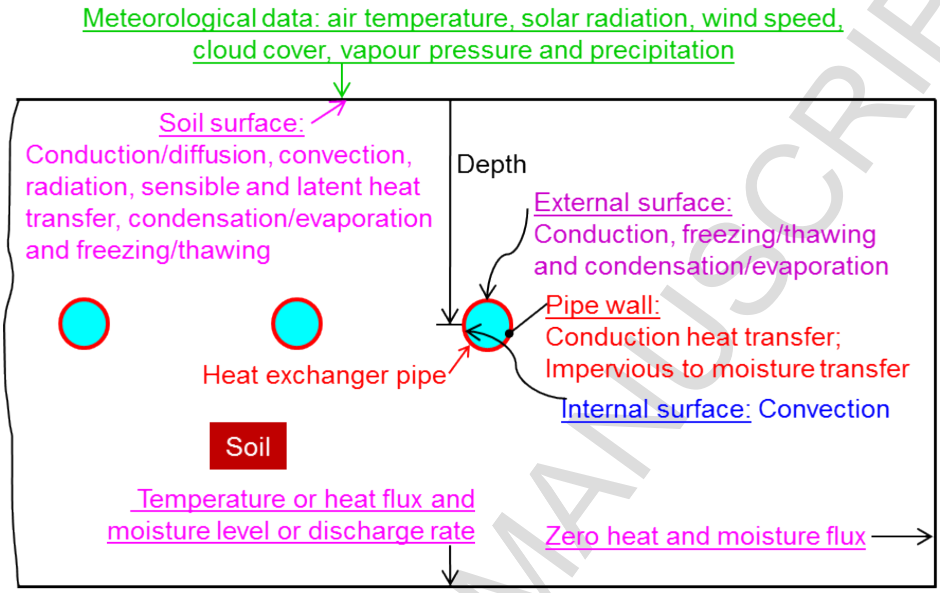


Fig. 1 Boundary conditions for simulation of heat and moisture transfer on a vertical plane normal to a horizontal ground heat exchanger

These one-dimensional equations are then numerically solved for multi-year heat and moisture transfer processes in soil until the differences in moisture and temperature at any depth for any time between two consecutive years become negligible. The same boundary conditions as described above are used. The numerical solution itself requires initial data for the soil temperature and moisture. Uniform initial values could be used for the whole domain. However, to speed up the processes, Equation (1) can be used for prescribing the initial soil temperature that varies with depth whereas varying initial moisture can be obtained from the following Richards equation [29]. It is a simplified form of Equation (13) for water flow in unsaturated soil without the influence of heat transfer and can be solved numerically or analytically for homogeneous soil [34] to begin with.

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z}\left(D_{\Theta,l}\frac{\partial \Theta}{\partial z}\right) + \frac{\partial K}{\partial z} \tag{15}$$

or, since $D_{\Theta,l} = K\frac{\partial \Psi}{\partial z}$, where Ψ is the matric potential (m),

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z}\left(K\left(\frac{\partial \Psi}{\partial z} + 1\right)\right) \tag{16}$$

2.4 Simulation procedure

Figure 2 shows the flow chart for the simulation of both 'coupled heat and moisture transfer' and 'heat transfer only' in soil with a ground heat exchanger. For a given site with known soil texture and atmospheric conditions, vertical temperature and moisture profiles are generated for multi-year heat and moisture transfer processes until the differences in temperature and moisture content at any depth (ΔT and $\Delta\Theta$) between consecutive years are less than a prescribed small value ε for any time of a year. The profiles are then used as initial conditions for transient simulation of coupled heat and moisture transfer in soil with the heat exchanger for specified boundary conditions and the properties of the heat exchanger and fluid inside. The impact on the dynamic thermal performance of a ground heat exchanger is finally assessed by comparing results from coupled heat and moisture transfer with those from heat transfer only.

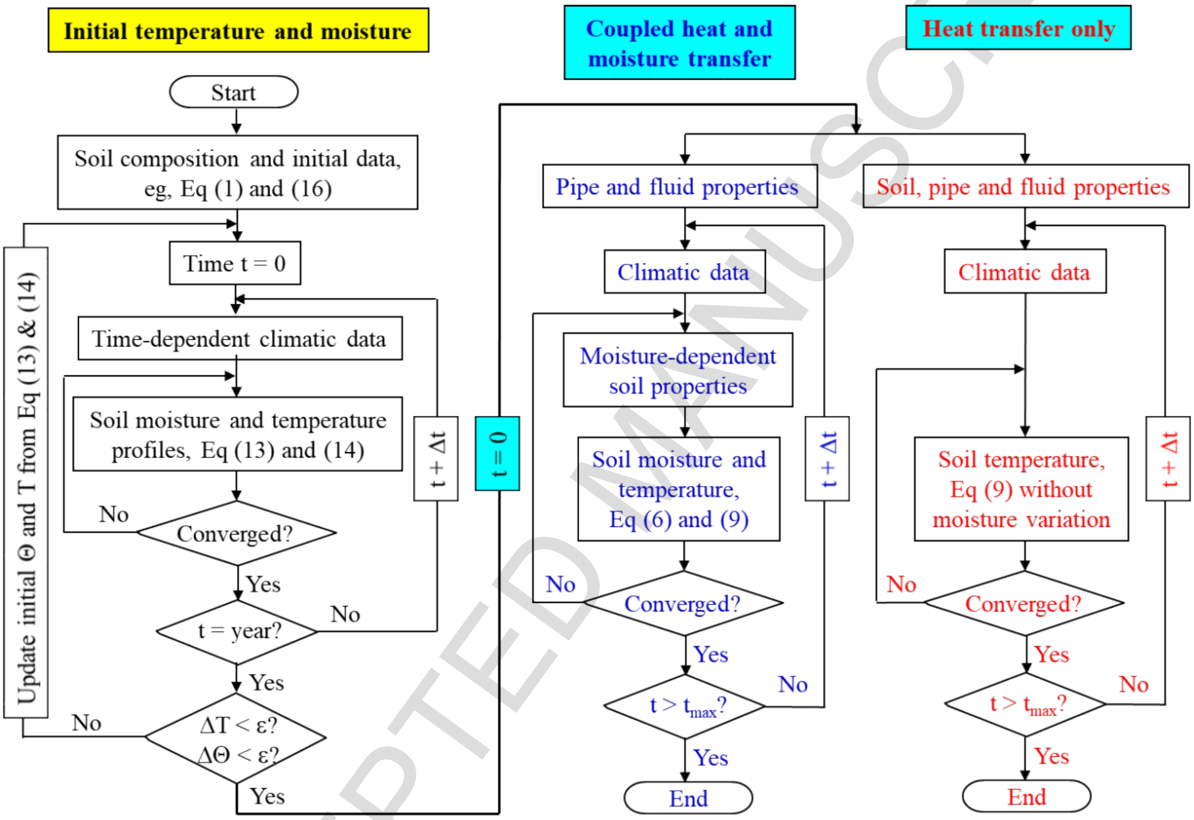


Fig. 2 Flow chart for numerical simulation of the impact of coupled heat and moisture transfer

In order to achieve an accurate and mesh-independent simulation while keeping the total mesh size within a reasonable number, a non-uniform mesh is used with fine cells distributed in areas near the heat exchanger and the soil surface where potential variations in heat and moisture transfer are large. Similar treatment is required for time steps with small sizes used at times when large changes in heat and moisture transfer occur such as the period right after the system is switched on or during and after intermittent water flow into soil due to rainfall.

3 VALIDATION

The numerical model is validated for simulation of transient heat transfer through a horizontal ground heat exchanger in soil with a loamy sand texture for heating in the Southern England from October to March by comparison with the results from a validated commercial software package Fluent [35]. The soil texture has a composition of 64.4% sand, 2.4% clay and 33.2% silt [32]. The saturation moisture content is 0.41 m^3/m^3. It is assumed that the depth of water table is 10 m and the fraction of vegetation cover is 0.5. The temperature of deep soil is 10°C. The ground heat exchanger is made of 40 mm high density polyethylene pipes and installed horizontally at 1.5 m deep. The refrigerant in the heat exchanger is a mixture of 65% water and 35% antifreeze operating at a fixed temperature of 1°C and velocity of 0.5 m/s.

Figure 3 shows the predicted heat transfer rate per unit length of the heat exchanger (specific heat transfer rate) using the two programs. It is seen that the results from the two programs agree very well with a maximum difference of less than 1% during the six-month period. As there is little difference between the two programs for heat transfer modelling, Fluent can also be used for predicting the performance of ground heat exchangers when temporal variation of soil properties is negligible and atmospheric and operating conditions can be simplified as constant or independent functions. However, the commercial software is developed mainly for solving fluid flow problems and is not easily adapted for simulation of coupled heat and mass transfer with spatiotemporally varying material properties and dynamic interactions between the horizontal ground heat exchanger, soil and atmosphere. For instance, simulation of the dynamic interactions in practice would require that the operating conditions for the refrigerant vary with the building load demand which is dependent on the varying soil and atmospheric conditions. The in-house program is specifically developed for solving this type of heat and mass transfer. In addition, it can generate more realistic initial conditions for simulation.

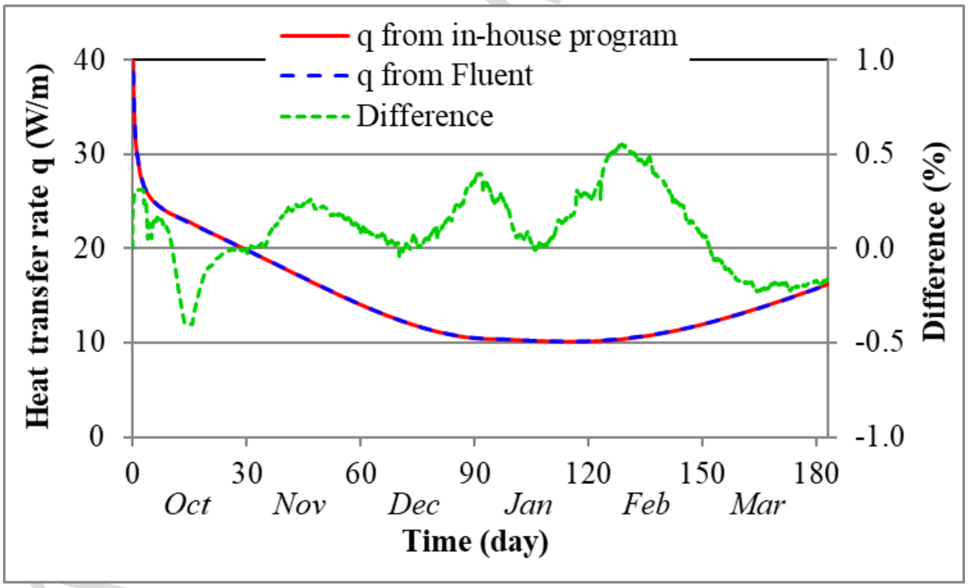


Fig. 3 Predicted heat transfer rate using in-house and Fluent programs

4 RESULTS AND DISCUSSION

To assess the impacts of coupled heat and moisture transfer and the initial conditions on the predicted thermal performance of a GSHP, the numerical method is applied to the prediction of the dynamic thermal performance of a ground heat exchanger in the same location and duration as above for validation. For heating application, the ground heat exchanger functions as an evaporator of the GSHP. The predicted performance of the heat exchanger with varying soil properties is compared with that under a set of constant soil properties. The effects of installation depth and soil texture are also investigated.

Results are first presented for the thermal performance of the heat exchanger installed at 1.5 m deep in loamy sand soil and then for the heat exchanger installed at different depths and in different types of soil.

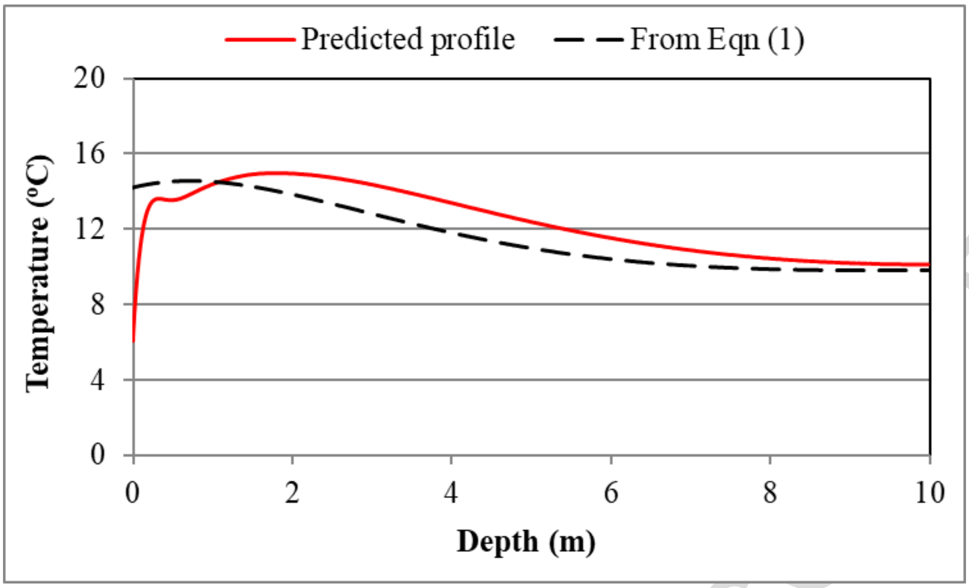
4.1 Heat exchanger at 1.5 m deep in loamy sand soil

The soil properties at the beginning of system operation are discussed first, followed by a comparison of the thermal performance of the heat exchanger installed at 1.5 m deep in loamy sand soil with and without moisture transfer.

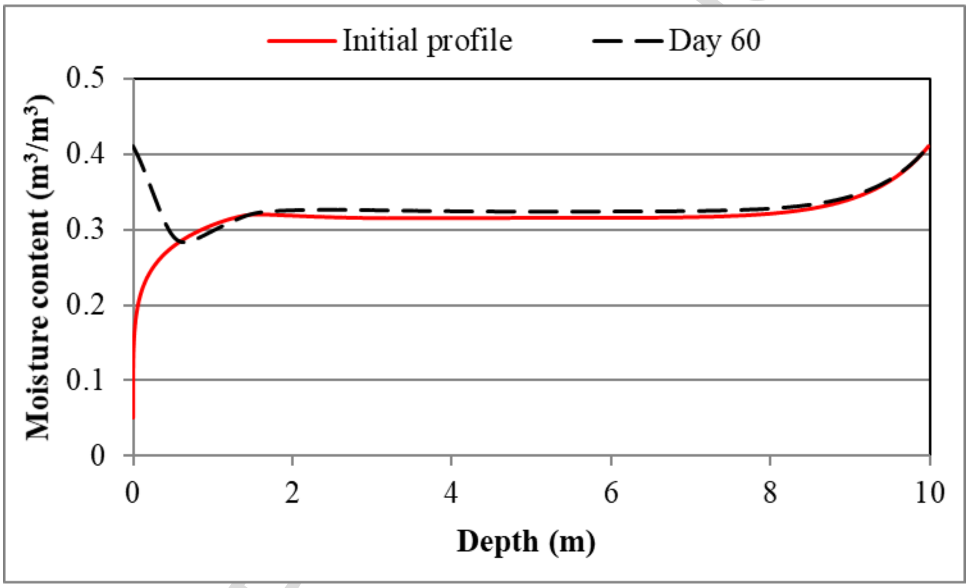
4.1.1 Initial soil properties

The predicted vertical variations of temperature and moisture content in loamy sand soil are shown in Fig. 4 for the first day (first midnight) of October as initial data. Fig. 4a also shows the soil temperature calculated from the analytical equation (Equation 1). There are significant differences in the initial temperature profiles between the numerical prediction and analytical solution. A much larger variation in the soil temperature can be observed from the numerical prediction than that calculated from the analytical solution, particularly up to a depth of about 2 m. The soil temperature is lower up to about 1 m deep but higher over this depth from prediction than calculation. The largest difference occurs at the top soil surface – the predicted temperature is about 6^{o}C during the night due to the radiation heat loss whereas Equation (1) would give rise to a much higher temperature of over 14^{o}C.

The soil surface is nearly dry without rainfall at the beginning of October and the moisture increases rapidly with depth to 0.32 m^3/m^3 at 1.5 m deep and then decreases slightly to 0.315 m^3/m^3 at about 3 m deep from where the moisture is nearly uniform up to 3 m from the water table depth. The moisture content for the 60th day (near the end of November) is also shown in Fig. 4b to demonstrate the accuracy for the moisture prediction. According to measurements [32], the soil moisture content could be higher nearer to the surface, e.g., about 0.36, 0.35 and 0.26 m^3/m^3 at 0.17, 0.37 and 0.75 m deep, respectively, between November and December. These are close to the corresponding values from the present prediction of 0.37, 0.32 and 0.28 m^3/m^3 for the 60th day after rainfall.



(a) Initial temperature



(b) Moisture content

Fig. 4 Predicted vertical variations of temperature and moisture in loamy sand soil

Figure 5 shows the predicted variations with depth of the density, specific heat and thermal conductivity of the soil at the beginning of October. At the top surface, the density, specific heat and thermal conductivity of dry soil are quite low at 1615 kg/m^3, 841 J/kgK and 1.07 W/mK, respectively. At the installation depth of the heat exchanger, their values increase by 16.6%, 56.5% and 76.8% to 1883 kg/m^3, 1316 J/kgK and 1.87 W/mK, respectively.

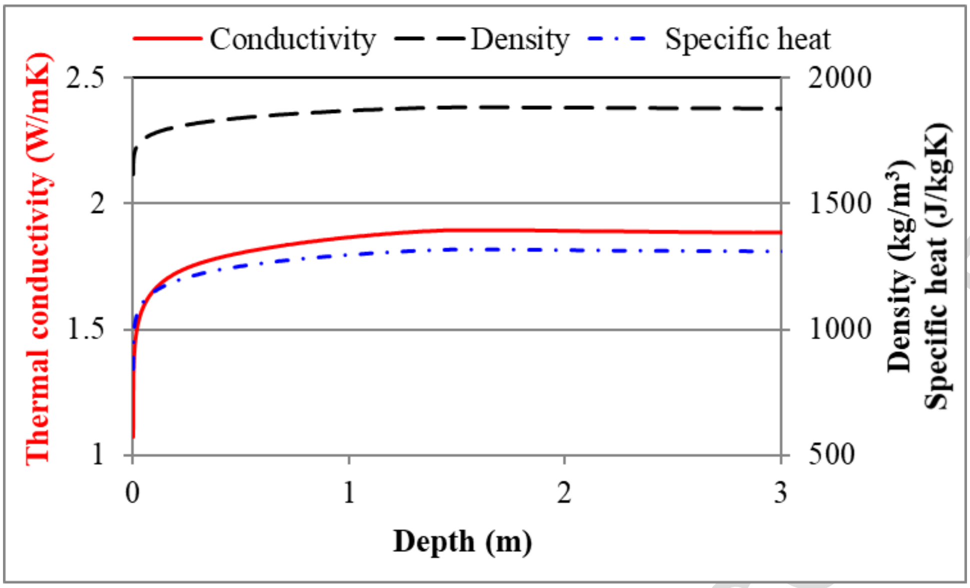


Fig. 5 Predicted variations in initial soil properties with depth

4.1.2 Performance with coupled heat and moisture transfer

Figure 6 shows the predicted heat transfer rate through the heat exchanger at 1.5 m deep in loamy sand soil together with the daily ambient air temperature and predicted temperature of undisturbed soil at the same depth for the heating season. The daily variation of air temperature is considerable at about 9°, 6° and 10°C at the beginning, middle and end of the heating season, respectively. The daily mean air temperature decreases gradually from October to December and then increases for the rest of the heating season. The soil temperature variation is also considerable throughout the heating season. The undisturbed soil temperature at the installation depth decreases from 14.9°C at the beginning of October to 5.8°C between January and February and then increases to 8.4°C at the end of March.

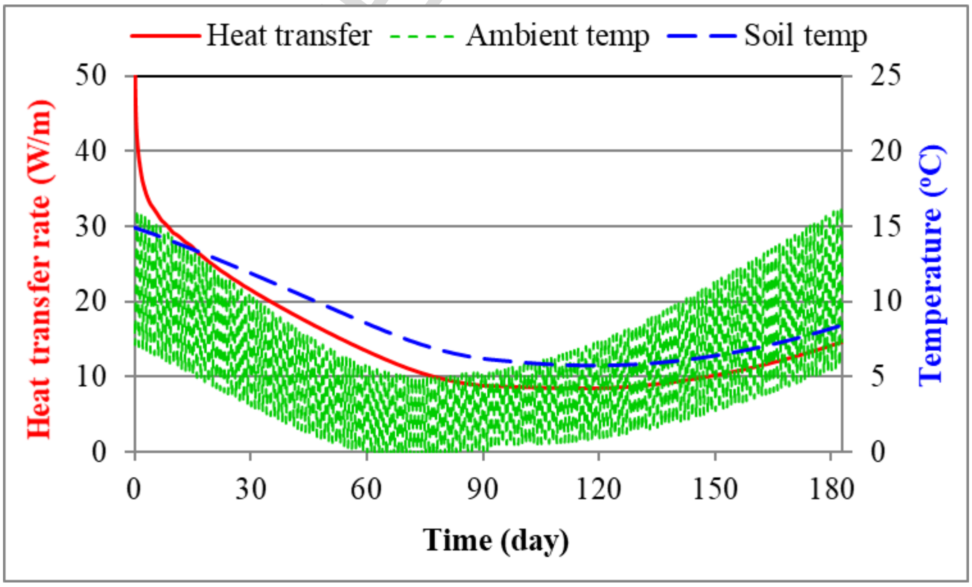


Fig. 6 Predicted heat transfer rate through the heat exchanger

The heat transfer rate per unit length of the heat exchanger is over 100 W/m for a few minutes at the beginning of the system operation when the temperature difference between the surrounding soil and cold fluid is at maximum. It decreases to 40 W/m at the end of the first day, 31 W/m at the end of the first week and 21 W/m at the end of October. The rate of heat transfer would decrease continuously to 13 W/m at the end of November and 9 W/m at the end of December and reaching a minimum of 8.5 W/m between the middle and end of January. The heat transfer rate then increases gradually to 14.7 W/m at the end of March due to increasing air and soil temperatures.

4.1.3 Performance with heat transfer only

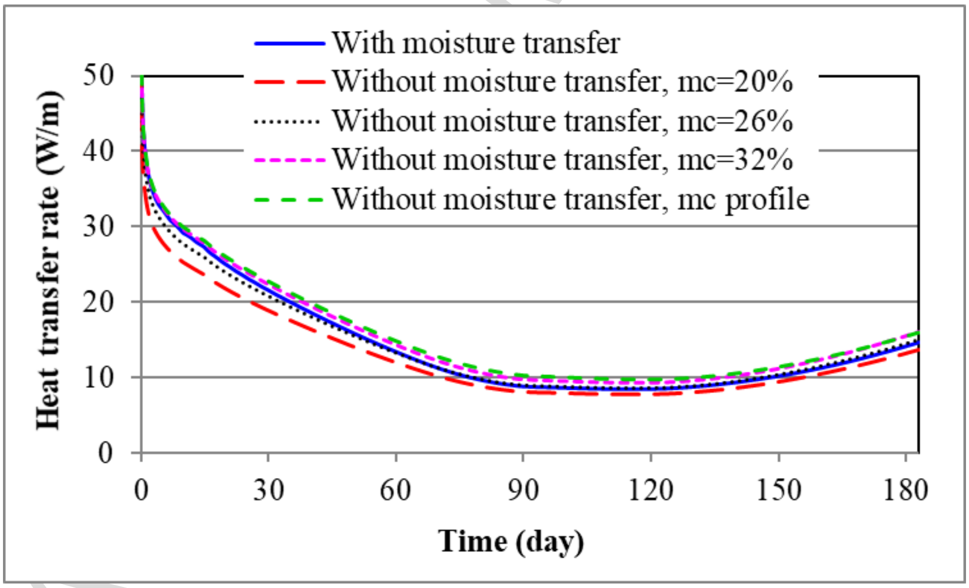
For simulation of heat transfer without involvement of moisture transfer, Equations (10) to (12) are also used for calculation of (constant) soil properties but with either a fixed value or a constant profile of moisture for the whole season. This model is denoted as the heat transfer model or the model with heat transfer only as opposed to the coupled heat and moisture transfer model or coupled model for short.

First, a fixed moisture content of 0.2 m^3/m^3 is used which was from one of the measurements at 1 m deep (the deepest measuring point) [32]. Because the fixed value of moisture is lower than that of deep soil and the values of soil properties increase with moisture, the predicted heat transfer through the heat exchanger without moisture transfer is lower than that with coupled heat and moisture transfer but their difference is not constant as shown in Fig. 7. The difference in the heat transfer rate (Difference for mc=20% in Fig. 7b) is about 13-14% for 20 days and decreases gradually to 12.4%, 10.5% and 8.2% towards the end of October, November and December, respectively. The difference remains nearly constant as the heat transfer rate bottoms out until mid-February and then decreases again afterwards.

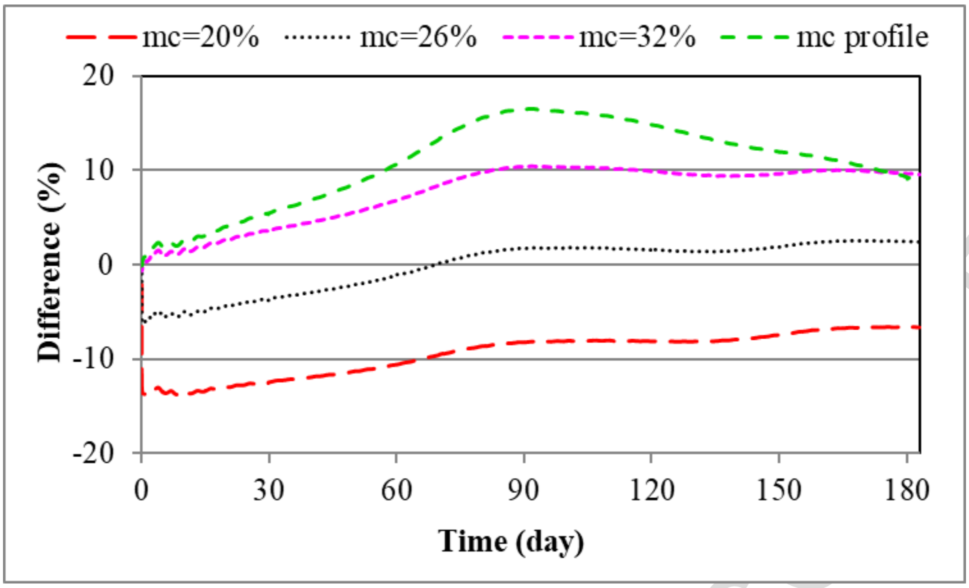
On the one hand, the difference between results from the two models would be reduced e.g. at the beginning if the moisture content of soil used for calculating the thermophysical properties in the heat transfer model was the same as that from the coupled heat and moisture transfer model at the installation depth. On the other hand, the changing difference means that even if a more accurate value of soil moisture e.g. from a measurement at the installation depth is used for calculating the soil properties or a single set of measured soil properties is used directly, dynamic or seasonal thermal performance of a ground heat exchanger cannot be predicted accurately using a model for heat transfer only, because of the spatiotemporal variation of soil properties. This is also demonstrated in Fig. 7 for a comparison with simulation using the heat transfer model with soil properties fixed at a mean moisture content of 0.32 m^3/m^3 (mc=32%) at the installation depth for the heating season. The predicted heat transfer rates with and without moisture transfer are the same at the beginning. The model without coupled moisture transfer would however over-predict heat transfer afterwards. The over-prediction increases with operating time up to about 10% at the end of December. In terms of seasonal average, using a low moisture content of 0.2 m^3/m^3 would result in under-prediction of heat transfer by 9.4% whereas using a high moisture content of 0.32 m^3/m^3 would lead to over-prediction by 7.7%.

One implication from the above comparisons is that when measured soil properties at the installation depth are used in a heat transfer model as currently implemented in most software for design and assessment if such data are available, the performance of a ground source heat pump would be over-estimated. It is possible to use a moisture content between these low and high values in order to reduce the seasonally averaged difference between the two models to a negligible magnitude, e.g. using 0.26 m^3/m^3 moisture (mc=26%) to reach a very small difference of about 0.1%. This could be one way to 'optimise' soil properties as input data – say equivalent soil properties - for system design with a method involving heat transfer only but still accounting for the likely impact of moisture transfer. However, even with such optimised input data, the system performance would be under-predicted for the first 10 weeks of the season with a maximum of 6% at the beginning and over-predicted for the rest of the season such that the absolute difference averaged for the whole season is over 2% for the same example. Besides, such optimal input data would vary with the type of soil texture and atmospheric conditions as well as the heat exchanger and its installation.

Further investigation indicates that using constant but non-uniform moisture would not improve the accuracy of prediction with a model for heat transfer only. When the spatially varying soil properties are calculated from the initial moisture profile, i.e. Fig. 4, for the heat transfer model, the temporal variation increases between the predicted heat transfer using the heat transfer model and that using the coupled model, as shown in Fig. 7b for the line with the mc profile. The difference (over-prediction) increases to a maximum of 17% in December and then decreases to 9% at the end of March with an average difference for the heating season of 11%.



(a) Heat transfer rate



(b) Difference from the coupled model

Fig. 7 Comparison between the predicted heat transfer rate through the heat exchanger with and without moisture transfer

The heat transfer rate through the heat exchanger is influenced not only by soil moisture but also by the initial soil temperature. Fig. 8 shows that when the initial soil temperature profile is replaced by Equation (1), the predicted heat transfer would decrease further from that for the soil properties estimated at a moisture content of 0.2 m^3/m^3. The difference (Difference 1) is about 5% at the beginning. It drops to 3.5% by the 5^{th} day and then rises to 5% near the end of October and just under 6% in December. From the beginning of January, the difference starts to decrease to 1.3% at the end of March. The variation pattern of the difference indicates the change of the soil temperature from initial data (Equation 1) to predicted temperature profiles at different stages under the influence of the heat transfer through the heat exchanger and interactions with atmosphere. The difference would diminish with further operation for three to four more months (after the 183^{rd} day shown in the figure) although continuous heating is unlikely needed for all these months.

Thus, the combined effect of coupled heat and moisture transfer and the initial temperature setting (referring to the heat transfer model with 0.2 m^3/m^3 soil moisture and Equation 1 for initial soil temperature) is an overall difference of round 17% for the first month's operation and this is also shown in Fig. 8 as Difference 2. The overall difference decreases to 13% and 8% at the end of December and March, respectively. The seasonal average difference is 13%.

The effect of the initial soil temperature appears not to be substantial for this case (maximum 6% for Difference 1 in Fig. 8). This is because the difference between the predicted and calculated temperatures at the installation depth happens to be small (= 0.67°C in Fig. 4a). The absolute temperature difference would be much larger at other depths, e.g. 1.1°C at 2 m deep, or at different times. For example, when the simulation is carried out for heating operation starting from the beginning of December, the calculated temperature at the 1.5 m depth is 1.67°C higher than the predicted value and the resulting difference in the heat transfer rate (higher value based on the analytical equation than the predicted temperature profile) is close to 20% for part of the first week as shown in magnitude as Difference 12 in the figure. The mean difference for the first month is 14%, decreasing to 5% for the second month. The difference decreases rapidly to 8%, under 3% and 1% at the end of the first, second and third month, respectively.

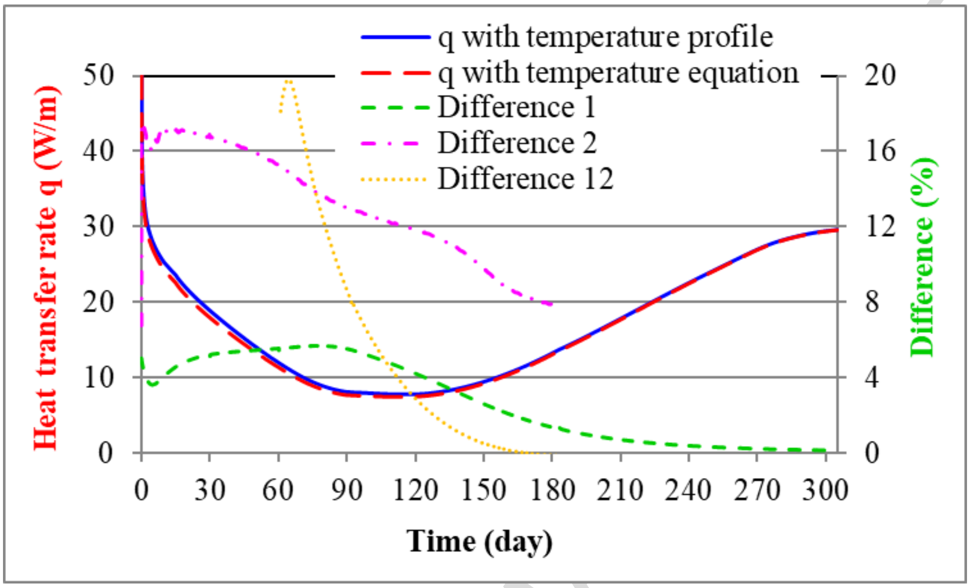


Fig. 8 Effect of initial soil temperature on the predicted heat transfer rate through the heat exchanger

4.2 Effect of installation depth

Because the soil temperature, moisture and associated properties vary with depth as well as time, the performance of a heat exchanger and the impact of the coupled heat and moisture transfer would depend on the installation depth. Fig. 9 shows the variation of the heat transfer rate for three installation depths and the difference from that for 1.5 m deep installation. Fig. 10 shows the predicted monthly specific heat extraction through the heat exchanger for five different installation depths. It can be seen that overall a heat exchanger installed at a deeper ground would have a larger heat transfer rate and the monthly mean heat extraction increases almost linearly with depth due to the higher soil temperature and moisture content during the most of heating season. However, their differences vary with operating time. At the end of October, the heat transfer rate for a heat exchanger installed at 1.5 m deep is 9% higher than that at 1 m deep but 6% lower than that at 2 m deep. The corresponding differences increase to 20% and 15% at the end of November and reach maxima of 26% and 22% near the end of December. From the 10th day of March, the heat transfer rate installed at a shallower ground increases faster such that the monthly mean heat extraction decreases with increasing depth (up to 1.8 m deep in March). The reason for the higher rate for the shallower installation is gradual warming up of soil by atmosphere from the new year.

The impact of the coupled heat and moisture transfer and installation depth also depends on the moisture content used for the calculation of the soil properties as shown in Fig. 11. When a low moisture content of 0.2 m^3/m^3 is used for calculating the soil properties, the performance would be under-predicted using the model for heat transfer only and the level of under-prediction is larger for deeper installation where the moisture content is higher in general in winter. Besides, the level of under-prediction generally decreases with operating time from a maximum of 14% in October to 8% at the end of March for the heat exchanger installed at 2 m deep. For the heat exchanger at 1 m deep, the level decreases from a maximum of 12% in October to a minimum of 3% in December and then increases slightly to 5% from February.

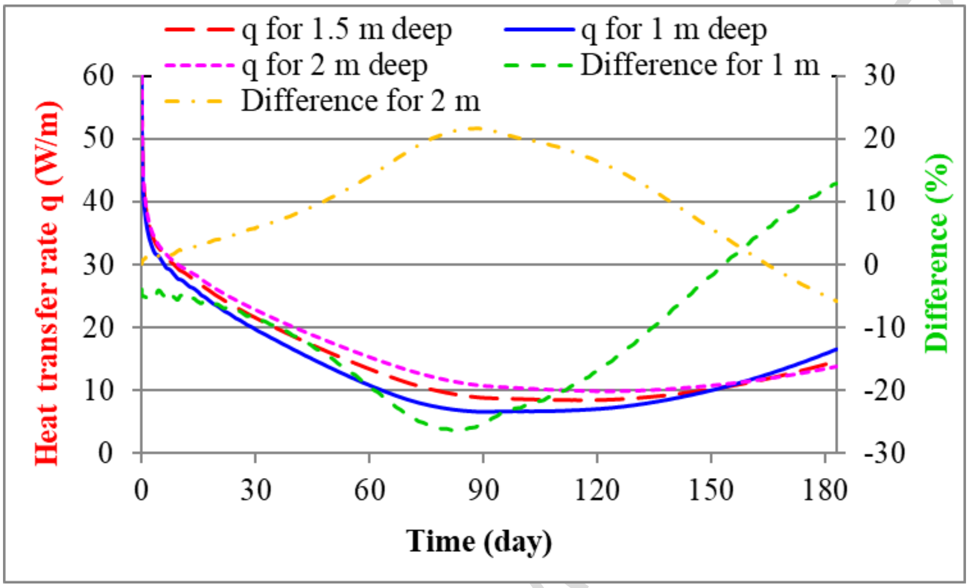


Fig. 9 Effect of installation depth on the predicted heat transfer rate through the heat exchanger

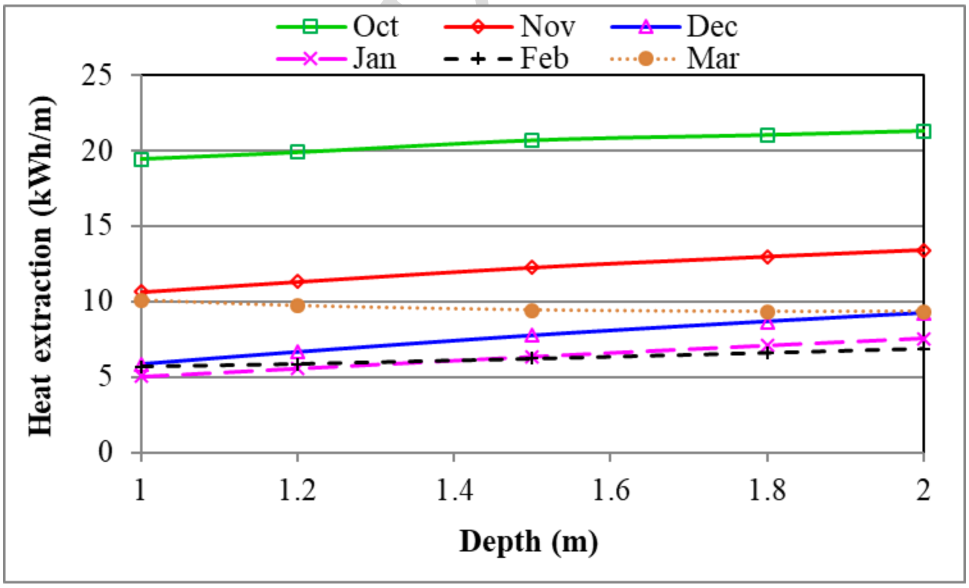
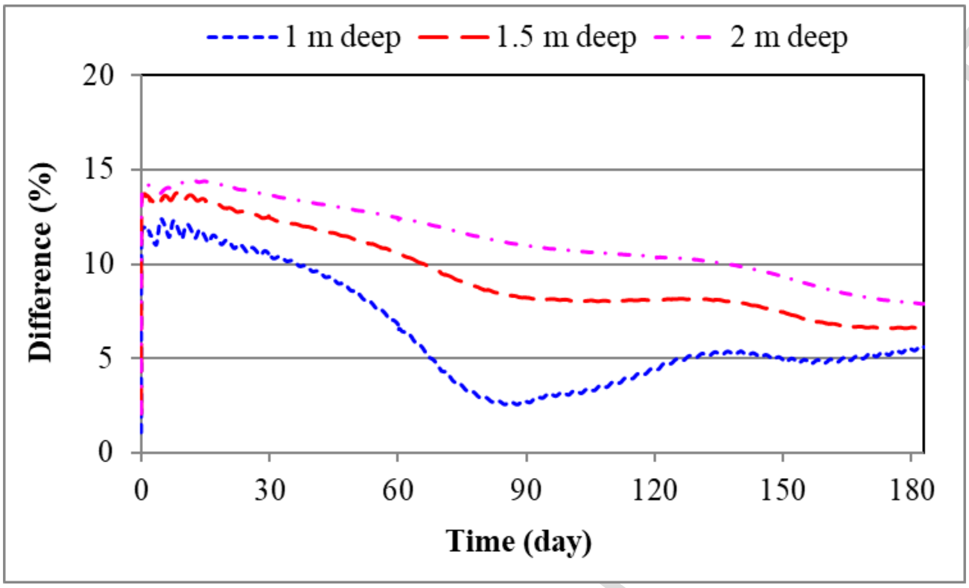
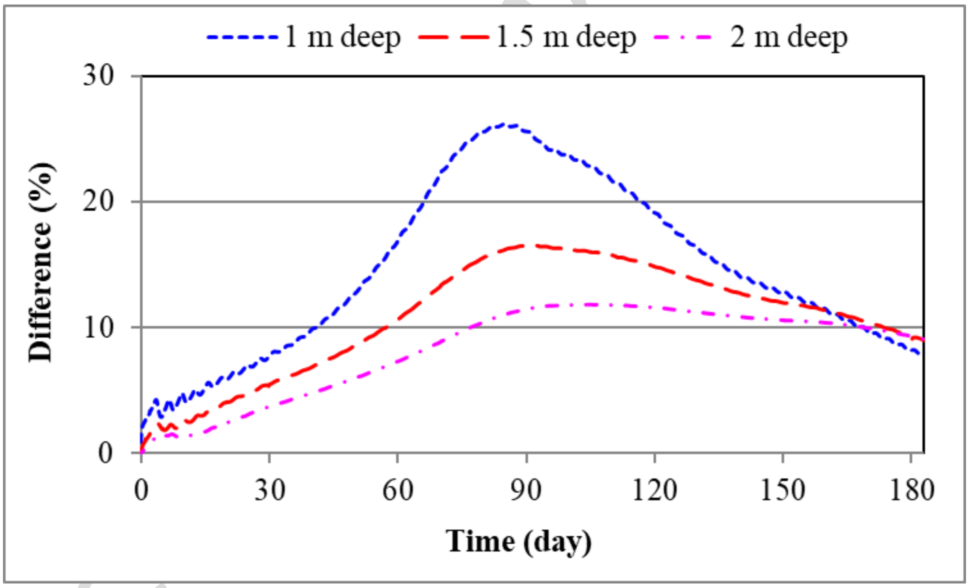


Fig. 10 Predicted monthly heat extraction at different installation depths

When the soil properties are calculated from the predicted moisture profile at the beginning of the season, using the model with heat transfer only would over-predict the performance and the level of over-prediction would be larger for shallower installation. The maximum difference reaches 26% a week before the end of December for 1 m deep heat exchanger compared with 12% two weeks later for 2 m deep one. Also, the level of over-prediction changes more with time for shallower installation such that it drops to 8% for the 1 m deep heat exchanger, 1% less than that for the 2 m deep installation, near the end of March.



(a) Under-prediction with a uniform moisture content of 0.2 m^3/m^3



(b) Over-prediction with an initial moisture profile

Fig. 11 Difference between the heat transfer predicted using the fully coupled model and that using the heat transfer model with fixed moisture for different installation depths

4.3 Effect of soil texture

To investigate the effect of soil texture on the heat transfer and the impact of coupling with moisture transfer, the soil texture is changed from loamy sand to either sand (with a composition of 92% sand, 3% clay and 5% silt) or clay loam (32% sand, 34% clay and 34%

silt). The saturation moisture content is 0.37 m^3/m^3 and 0.45 m^3/m^3, respectively, for sandy and clay loam soils compared with 0.41 m^3/m^3 for loamy sand soil. It is assumed that the heat exchanger is installed at the same depth of 1.5 m. The initial moisture content at the installation depth is approximately 0.29 m^3/m^3 and 0.39 m^3/m^3 for sandy and clay loam soils, respectively, whereas it is 0.32 m^3/m^3 for loamy sand soil. The corresponding thermal conductivity is about 2.48 and 1.44 W/mK for sandy and clay loam soils, respectively, compared with 1.87 W/mK for loamy sand soil, and the thermal diffusivity is 0.53, 0.75 and 1.01 x 10^{-6} m^2/s for clay loam, loamy sand and sandy soils, respectively.

Figure 12 shows the heat transfer rate through the heat exchanger in three different types of soil and the difference from the loamy sand soil. Because the thermal conductivity/diffusivity of sandy soil is higher than that of loamy sand, the heat transfer rate through the heat exchanger is 14% to 21% higher in sandy soil than in loamy sand soil with a seasonal average of 17%. In contrast, the heat transfer rate is 12% to 19% less in soil with a clay loam texture and the mean seasonal difference is 14.5% due to its lower thermal conductivity and diffusivity than those in loamy sand soil.

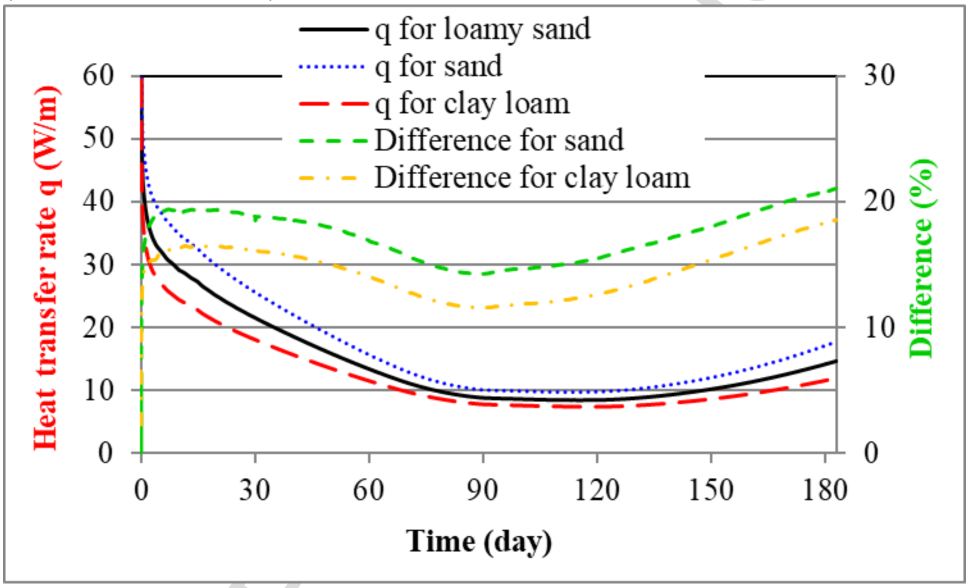
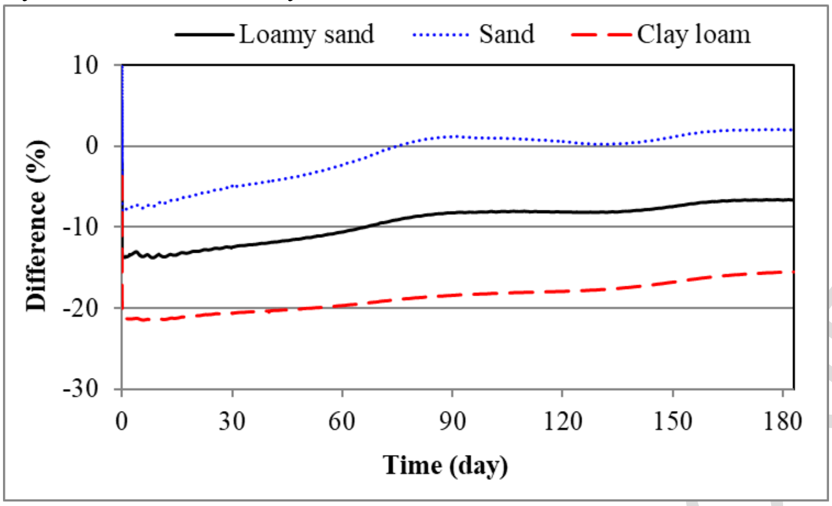
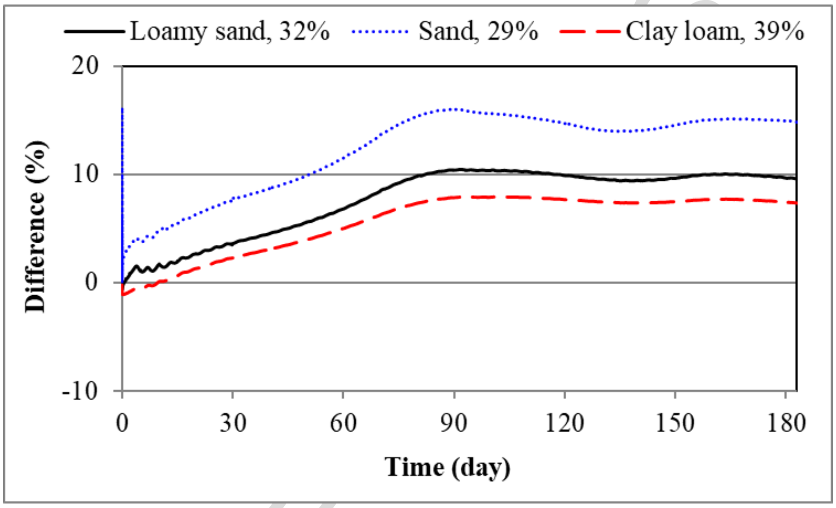


Fig. 12 Effect of soil texture on the heat transfer rate through the heat exchanger

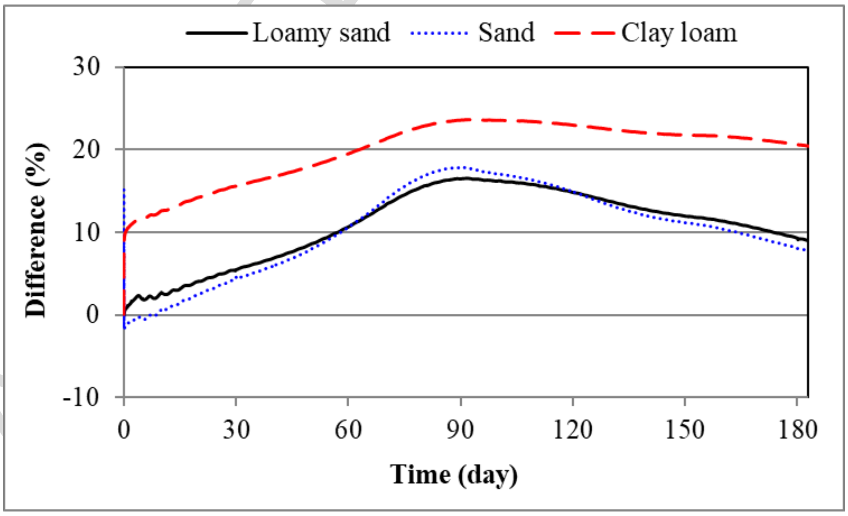
The impact of simulation with coupled heat and moisture transfer is dependent on the choice of initial moisture for each type of soil. Using the model with heat transfer only and with soil properties calculated from a uniform moisture content of 0.2 m^3/m^3, the heat transfer rate would be under-predicted considerably for clay loam soil with a maximum value of 22% near the beginning of operation, as shown in Fig. 13a. For sandy soil it would be under-predicted in the early period (with a maximum value of 8%) but then slightly over-predicted in the later period of the season. The level of under-prediction for the clay loam soil decreases with the increase in operating time with a mean value of 19% but for the sandy soil the amount of under-prediction nearly cancels out the amount of over-prediction with a net difference of about 1% only. When the initial moisture content at the installation depth is used for calculating the soil properties, the heat transfer model would over-predict the heat transfer rate for each type of soil in almost all the time (Fig. 13b). The average level of over-prediction is 12% for sandy soil and 6% for clay loam soil.



(a) With a uniform moisture content of 0.2 m^3/m^3



(b) With a uniform moisture content for each type of soil (e.g. 39% = 0.39 m^3/m^3)



(c) With initial moisture profiles

Fig. 13 Effect of soil texture on the difference in heat transfer between the fully coupled model and the model with heat transfer only

The moisture variation in clay loam soil is larger both spatially (up to the depth of the heat exchanger) and temporally. As a result, the impact of moisture transfer is much larger when comparing results from the coupled model with those from the heat transfer model with constant but spatially varying soil properties calculated from the initial moisture profile and soil composition (Fig. 13c). The model with heat transfer only would over predict the thermal performance significantly with a peak difference of 24% in December and average difference for the heating season of 20%. For the sandy soil, without coupling with moisture transfer, the heat transfer rate would be under predicted for the first week or so but over predicted for the rest of the season. The maximum over-prediction is 18% in December compared with 17% for the loamy sand soil. The average over-prediction for the whole season is about 10% for the sandy soil which is not far from the value for the loamy sand soil (11%).

5 CONCLUSIONS

A numerical method has been developed to generate initial soil moisture and temperature profiles and predict the dynamic thermal performance of ground heat exchangers for ground source heat pumps. The profiles are able to account for the diurnal variations in atmospheric and soil conditions and heterogeneity of soil properties. The impacts of the initial profiles and coupled soil heat and moisture transfer have been investigated.

The rate and amount of heat transfer through a heat exchanger are dependent on the installation depth and soil texture. The predicted heat transfer rate generally increases with installation depth but could decrease with increasing depth in a later part of a heating season due to rising air and soil temperatures. For a heat exchanger installed at 1.5 m deep, the seasonally averaged heat transfer (mean heat transfer) is 17% higher in sandy soil and 14.5% lower in clay loam soil than in loamy sand soil.

The impact of soil moisture transfer is found to be significant for the predicted performance of a ground heat exchanger. The impact varies with operating time as well as soil texture and installation depth of the heat exchanger. Therefore, accurate prediction of the seasonal performance of a ground heat exchanger requires the consideration of coupled heat and moisture transfer. Without coupling with moisture transfer, a heat transfer model using a low moisture content of 0.2 m^3/m^3 for calculating soil properties would under predict the mean heat transfer through a 1.5 m deep heat exchanger by 22%, 14% and 8% for clay loam, loamy sand and sandy soils, respectively. By contrast, if a high moisture content of 0.32 m^3/m^3 is used, the mean heat transfer would be over predicted by 8% for loamy sand soil. Besides, a model involving heat transfer only cannot predict the seasonal performance of a heat exchanger accurately even with precise values of soil properties from measurements. For example, using 'measured' data at the installation depth for a method involving heat transfer only would lead to over-prediction of the seasonal performance by approximately 6%, 8% and 12% in clay loam, loam sand and sandy soils, respectively. Even with a set of spatially varying soil properties in the heat transfer model, the mean heat transfer would be over predicted by 20%, 11% and 10% for clay loam, loamy sand and sandy soils, respectively. The maximum over-prediction would approach 24%, 17% and 18% in clay sand, loamy sand and sandy soils, respectively.

The performance is also influenced by the initial soil temperature. The difference in the predicted heat transfer through a 1.5 m deep heat exchanger in loamy sand soil would be up to 6% using a temperature profile suitable for inhomogeneous soil compared with an analytical equation for homogeneous soil. The heat transfer difference could be much larger for a heat exchanger installed at different depths and/or with heating operation at different starting times such that the temperature difference is larger at the installation depth between the predicted profile and analytical solution.

Although the impacts of initial conditions and coupled heat and moisture transfer are demonstrated for a horizontal ground heat exchanger, the same methodology can be used for assessing vertical heat exchanger systems, in particular those installed in shallow ground such as energy piles or foundation heat exchangers.

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Highlights

- Coupled heat and moisture transfer in soil-ground heat exchanger system
- A methodology to generate soil moisture and temperature profiles
- Significant impact of soil moisture on thermal performance of GSHP
- Influence of installation depth and soil texture
- Importance of accurate initial conditions for transient flow simulation